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Evaluating Effects of Opening Provisions in Courtyard on the Performance of Indoor Thermal Environment

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Abstract: *A courtyard's thermal functionality depends on various factors, including its opening. The Uniform Building By-Law of 1984 specifies a minimum requirement of 10% openness per total floor area. Nonetheless, it is still unclear if this requirement is sufficient and effective in ensuring the comfort for indoor spaces surrounding an air well. Therefore, this study aims to investigate the effect of opening provisions on the indoor thermal environment by assessing the indoor thermal condition of an air well-type courtyard terrace house. Field measurements were conducted to measure the thermal environmental parameters of a living room and a bedroom in the selected house connected directly to the courtyard. The findings are compared and analysed according to previous literature and the ASHRAE and MS2680:2017 standards. The result indicated that the living room has a high temperature with static air movement that causes heat to be trapped inside the room. This raises the question of the current opening provision that may render a courtyard effective in moderate indoor thermal performance.*

Keywords: Indoor Thermal Environment, Air-Welled typed Courtyard, Terrace House, Opening, Uniform Building By-Law

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1. Introduction

In a hot-humid climatic region such as Malaysia, numerous studies have demonstrated that naturally ventilated residential buildings, such as terrace houses, often exhibit less than acceptable thermal performance in their indoor environment. Poor indoor thermal environments caused by heat accumulating in building interiors (Sadafi et al., 2008), have led to dissatisfaction and discomfort among occupants. This has been a recurring issue experienced by residents of terrace houses (Al-Obaidi & Woods, 2006; Azzmi & Jamaludin, 2014; Bornoma & Adediran, 2017; Nugroho et al., 2007). As a result, residents resort to mechanical cooling in pursuit of better thermal conditions (Kubota et al., 2009; Toe and Kubota, 2015). While it offers cool and dehumidified air, such a mechanical system negatively impacts the environment through emissions of hazardous gases and high annual energy consumption in the housing sector (Moghimi et al., 2014).

To address this thermal environment issue and the high energy consumption, building consultants and designers incorporate low-energy movement and passive design strategies that

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reduce building energy consumption, raise user awareness, and provide a comfortable environment (Nugroho et al., 2020). Among other strategies, courtyards were introduced into residential building designs. Courtyards are a passive design strategy that may efficiently improve the microclimate conditions of urban areas (Zamani et al., 2018). It has been proven to reduce indoor air temperature (Bornoma & Adediran, 2017; Nugroho et al., 2020; Sadafi et al., 2011). However, a well-functioning courtyard requires careful consideration of various crucial elements, including opening size. The effectiveness of a courtyard as a strategy greatly depends on the opening design and details to ensure appropriate airflow patterns (Rajapaksha et al., 2003). Multiple authors, including Nugroho et al. (2020), Rajapaksha et al., (2003), and Zamani et al. (2018), have cited openings as an influential factor that significantly affects the microclimatic function of courtyards. The opening configuration, particularly its size, is even specified in the Uniform Building By-Law (UBBL) 1984, which mandates minimum opening provisions per floor area for compliance and enforcement by local authorities and building experts (Idowu et al., 2016). This regulation emphasizes the importance and value of openings, especially in residential buildings.

However, a recent field study by Leng et al. (2021) raised questions on the adequacy of the minimum requirement of 10% openings per total floor area of a room stipulated under UBBL 1984. Based on the findings obtained, it was ineffective and insufficient in creating a comfortable and desirable thermal environment. Furthermore, it remains unclear whether the current laws governing provisions for opening are sufficient for Malaysian homes to attain the ideal ventilation rate (Ibiyeye & Zalina, 2015; Idowu et al., 2016). This highlights the necessity for further investigation into the opening provision requirements.

Therefore, this study intends to investigate the influence of opening provisions on the indoor thermal environment of an air-welled terrace house. To accomplish this aim, several objectives were established: i) To identify the opening provision of rooms adjacent to the air-welled type courtyard in the selected terrace house; ii) To determine the current indoor thermal environment of rooms adjacent to the courtyard; and iii) To evaluate the effects of opening on the indoor thermal environment of rooms connected to the air-well. The main theories and body of research in this field are first explained, and then the steps of the methodologies employed in the study are covered. The study's findings are then presented and discussed, and the paper concludes with some suggestions for additional research.

2. Methodology

To accomplish the research objectives, the research methodology used field measurement as a method of data collection. Through a field study, the indoor thermal environmental parameters consisting of air temperature, air velocity, and relative humidity of rooms adjacent to the air-well-type courtyard were measured using intricate equipment. The rooms are then assessed and compared to prior research findings and the thermal comfort model in ASHRAE and MS2680:2017.

Description of selected terrace house

According to the National Property Information Centre (NAPIC), terrace houses accounted for 41% of residential property sales in Malaysia in 2020. In 2020, terrace houses continued to be the most common typology. Table 1 further revealed that the majority of earlier researchers primarily used double-story terrace buildings as their case studies. As there are few research done exclusively on single-story terrace dwellings, this suggests the necessity to fill the vacuum in the literature. An urban site was selected due to the higher likelihood of experiencing higher temperatures in such a location. A single-story terrace house with an air-well-type courtyard in Puncak Iskandar, Bandar Seri Iskandar, was selected as the case study. Furthermore, Bandar Seri Iskandar was found to be a city characterized by higher solar radiation levels throughout the year compared to other cities in Malaysia (Mohammad et al., 2020).

Table 1: Tabulation data for past studies on terrace houses in Malaysia

Author	Terrace House Type	
	Single-storey	Double-storey
Tuck et al., (2020)		●
Leng et al., (2019)	●	
Tuck et al., (2019)		●
Gamage et al., (2017)		●
Idowu et al., (2016)		●
Chung et al., (2015)	●	
Ibiyeye & Zalina, (2015)		●
Sadafi et al., (2011)		●

Puncak Iskandar comprises bungalows, terrace houses, and semi-detached houses. Among these properties, there are only four (4) distinct types of terrace houses: three of them are single-story, whereas the remaining are double story (Table 2). Only one of the three single-story terrace houses featured the passive design strategy, an air-welled-type courtyard. An intermediate single-story terrace house, located nearby other housing units within the residential area, was chosen as the case study.

Table 2: Selection of Case Study

	Type 1	Type 2	Type 3	Type 4
Single storey	●	●	●	
Double storey				●
Presence of Air-Welled Type Courtyard	●			

Figure 1: The Air-welled type courtyard Terrace House Selected and its Orientatio

Field Measurement Procedure

The fieldwork study was conducted within five days in January under common intermediate sky (30-70% cloud cover) for outdoor and indoor conditions (Ahmed et al., 2011; Sadafi et al., 2011). Both indoor and outdoor measurements were recorded simultaneously on the same day and time, from 7 a.m. until 7 p.m. This twelve-hour time range was selected to capture the average duration for which terrace house residents typically open their windows (Kubota, 2006; Kubota & Ahmad, 2005).

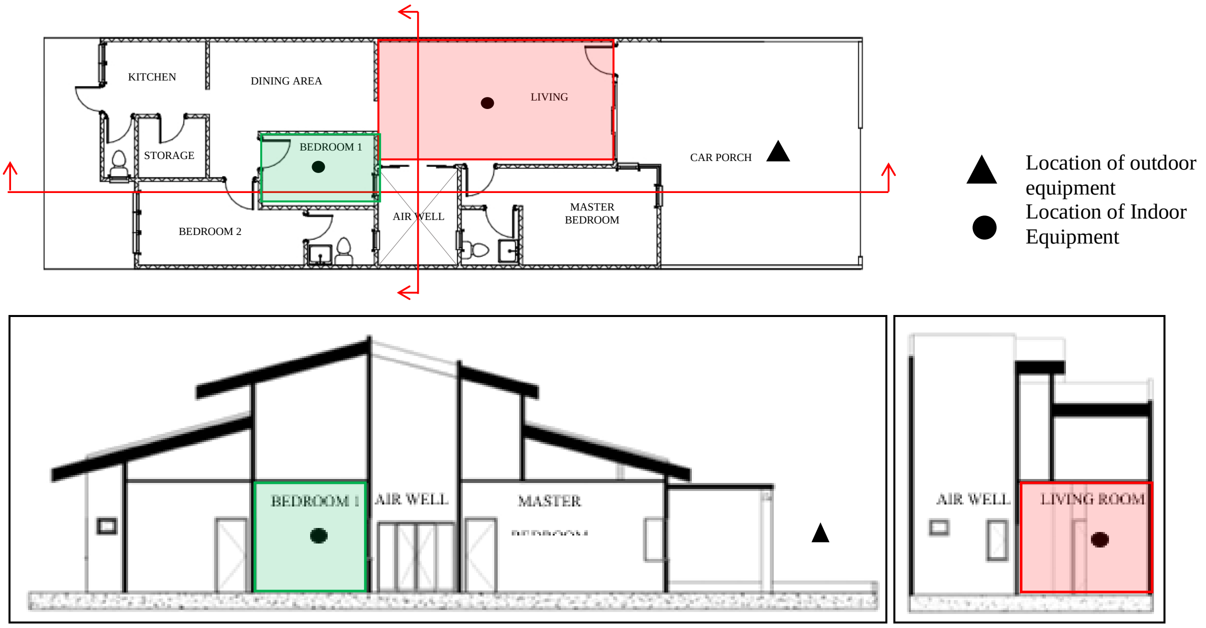

Figure 2: Floor Plan and Section of Air-Welled-Type Courtyard Terrace House indicating placement of Measuring Instruments.

Table 3 exhibits the equipment used for the field measurements. The first set of the Thermal Multi Data Logger and its sensors were carefully installed outdoors, 5 metres away from the building envelope and without any shade. This will provide the measures of temperature, humidity and air velocity outside of the house for comparison. Due to their direct connections to the air well, bedroom 1 and the living room were used for the indoor field measurement. The parameters measured were air temperature, air velocity, and relative humidity. All openings connected to the air well were left open. Additionally, all forms of lighting, ceiling fans, and air conditioners were switched off during the entirety of the measurement process. The rooms were left vacant and unfurnished in order to maintain accuracy and minimise the impact of other factors. The second set of Data loggers was positioned in the centre of the living room as it was considered a suitable placement to capture the representative indoor thermal conditions (Stazi et al., 2017). Meanwhile, velociCalc and its probes were placed in bedroom 1. All sensors and probes were mounted 1.5 metres above the ground and free from any obstruction that might cause interference. All readings were recorded at a 10-minute interval (Ahmed et al., 2011; Sadafi et al., 2011).

Table 3: Summary of instruments used during field measurement procedure.

Space	Data Type	Equipment	Setting Positions of Equipment	Descriptions
Bedroom 1	Air Temperature Relative Humidity Air velocity	• VelociCalc Air Velocity Meter	1.5 m from the floor level in the centre of the room	Purpose: To determine the current indoor thermal environment of terrace house with an air-welled type courtyard
Living Room	Air Temperature Relative Humidity Air velocity	• Thermal Multi Data Logger -Delta Ohm HD31 • Air temperature and Relative Humidity Sensor • Omnidirectional Hotwire probe		
Outdoor	Air Temperature Relative Humidity Air Velocity Solar Radiation	• Thermal Multi Data Logger – Delta Ohm HD31 • Air temperature and Relative Humidity Sensor • Directional Hotwire Probe • Pyranometer	1.5m from floor level, 5m away from terrace house building frontage, without shade	Purpose: Taken as a controlling factor compared to the measured indoor thermal environmental parameter

3. Findings

Indoor Thermal Environment of Rooms Adjacent to the Air-Welled Type Courtyard

Identifying the Opening Provisions of Selected Rooms

Before conducting the data collection stage, it was necessary to identify the opening provisions of the selected rooms in the terrace house. These opening provisions were calculated using the formula established in the UBBL 1984 (Uniform Building By-Law). The formula below was used to determine the opening/floor area percentage:

$$\text{Percentage of opening/floor area (\%)} = \frac{\text{Opening Area } (m^2)}{\text{Floor Area } (m^2)} \times 100$$

The opening and floor areas of the selected living spaces were recorded in Table 4. It was discovered that neither room's percentage of the opening provisions met the requirements specified in the UBBL.

Table 4: Percentage of Opening Provisions of Rooms Adjacent to the Air-Welled Type Courtyard

Living Spaces	Floor Area (m^2)	Opening Area (m^2)	Percentage Opening Area/Floor Area (%)
Living Room	25.5	2.2	8.6
Bedroom 1	7.7	0.72	9.4

Comparison of the Indoor Thermal Environmental Parameters for an Average of 3 Days

It is necessary to analyse the average readings over three days for all recorded thermal environmental factors to determine the air-welled terrace house's initial conditions with its current opening setting. The comparative study was intended to ascertain the variation in the readings between the rooms. In this study, the 3-day average readings of all recorded data on thermal environmental parameters represented a one-day trend. The findings of the field measurements conducted in the living room, first bedroom, and outdoors are summarised in Table 5.

Table 5: Summary of Average 3-Days Reading of Thermal Environmental Factors of Outdoor, Bedroom 1 and Living Room.

Parameter	Air Temperature (◦C)			Relative Humidity (%)			Air Velocity (m/s)		
	Outdoor	Bedroom 1	Living Room	Outdoor	Bedroom 1	Living Room	Outdoor	Bedroom 1	Living Room
Min.	23.9	27.7	27.7	33.0	67.4	63.4	0.01	0.01	0.01
Max.	34.2	28.8	30.4	82.0	71.8	72.3	0.90	0.02	0.13
Average	30.0	28.3	29.4	54.1	69.3	67.6	0.42	0.01	0.02

Figure 3 illustrates the pattern of the outdoor, living area, and bedroom 1's 3-day average air temperature data. From 7 a.m., the outdoor air temperature increased gradually with slight fluctuations until 3.40 p.m., when the reading began to decline. Even though the average indoor air temperature of both rooms similarly increased in the morning, the average air temperature in the living room consistently rose to a higher level than that in bedroom 1. As shown in Table 5, the average 3-day reading of the outdoor air temperature recorded at 30°C was higher than bedroom 1 and the living room's average. The average air temperature readings for the living room and bedroom 1 were 29.4°C and 28.3°C, respectively. It resulted in a slight difference of 1.1°C. The difference between the indoor spaces' average air temperatures was minor yet significant.

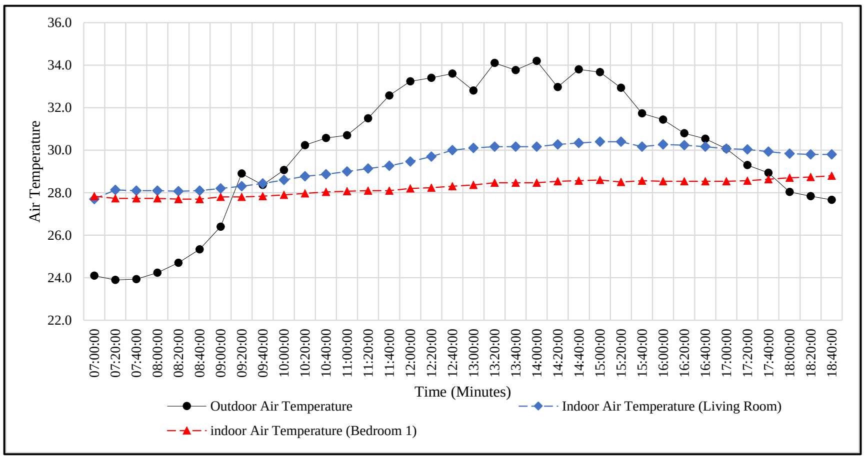

Figure 3: Average 3-Days Air Temperature for Outdoor, Living Room and bedroom 1.

The average outdoor relative humidity over three days was reported at 54.1%. Meanwhile, the relative humidity in the living room was 67.6%, whereas the average indoor relative humidity in bedroom 1 was 69.3%. The relative humidity in the living room was, on average, 1.7% lower than in bedroom 1, a negligible difference. Figure 4 shows the pattern of relative humidity in the living room and bedroom 1, where there is a noticeable variation. From 7 a.m. until noon, the average outdoor relative humidity declined substantially. Then, from 1 p.m. to 7 p.m., it increased gradually with slight fluctuations. Simultaneously, the readings of both rooms revealed certain similarities at specific points, particularly in the morning from 7 a.m. to 9:20 a.m. and in the evening at 6. The relative humidity of both spaces gradually decreased, specifically from midday until 3 p.m. The living room and bedroom 1 recovered by 3 p.m. and increased reading.

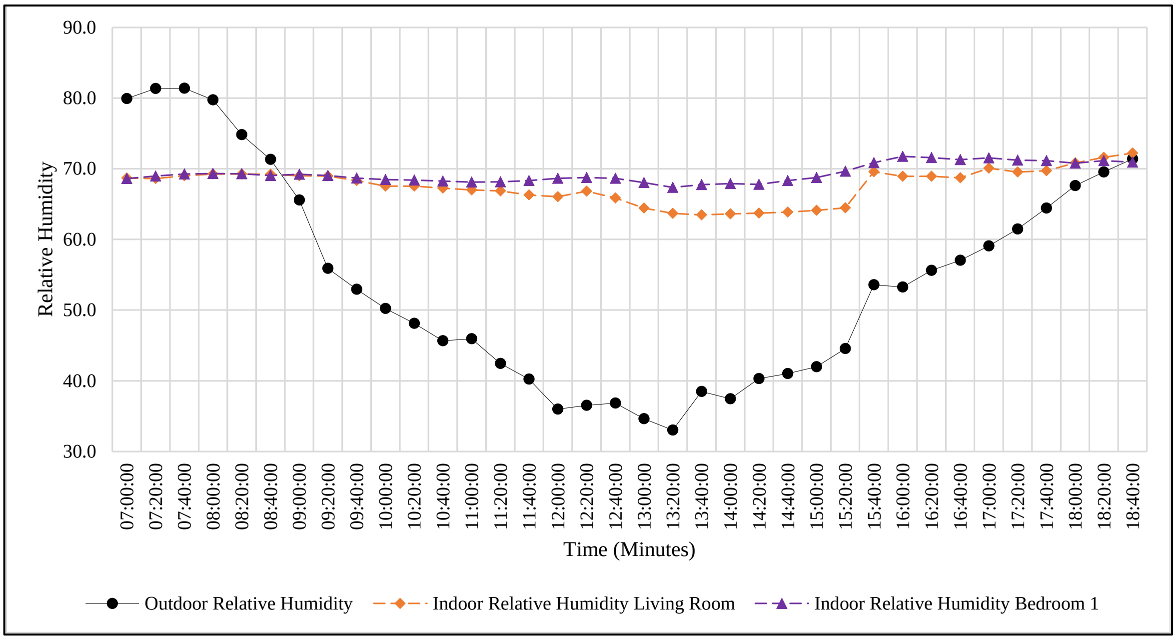

Figure 4: Average 3-Days Relative Humidity for Outdoor, Living Room and bedroom 1

The average indoor air velocity of bedroom 1 and the living room was 0.01 m/s and 0.02 m/s, respectively, while the average outdoor air velocity was 0.42 m/s (Table 5). The outdoor and indoor air velocities varied around 0.4 m/s. Figure 5 demonstrates how the outdoor air velocity appears to fluctuate wildly throughout the monitoring period. However, the indoor air velocity graph in both rooms showed a generally constant and steady pattern, in contrast to the outdoor air velocity trend. While the living room had minor fluctuations between 7 a.m. and 10:20 a.m. and in the evening between 3:20 p.m. and 6:20 p.m., bedroom 1's air velocity remained relatively constant. At certain times, the average reading of the living room occasionally exceeds the average air velocity reading of bedroom 1.

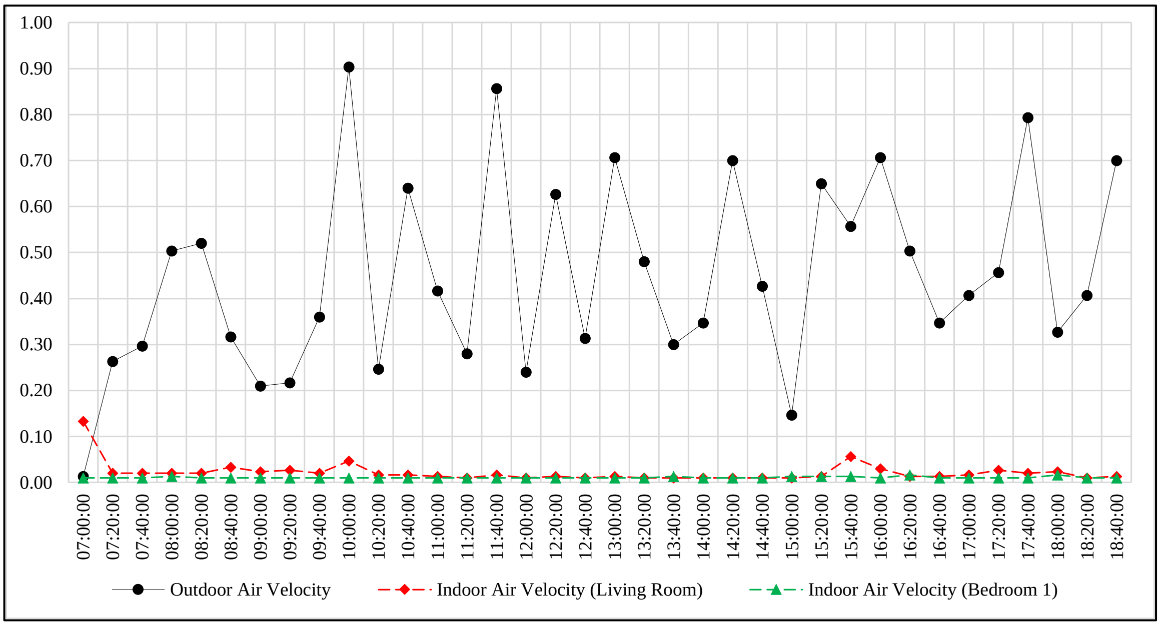

Figure 5: Average 3-Days Air Velocity for Outdoor, Living Room and bedroom 1

Evaluation of the Thermal Environment of Bedroom 1 and Living Room

Table 6 compares the thermal environmental parameter measurements made in the living room and bedroom 1 to past research studies and to the standards established by the thermal comfort model, namely ANSI/ASHRAE Standard 55-2017 and MS2680:2017.

The average air temperature of bedroom 1 complied with most of the standards, while the living room did not. The living room's air temperature was only appropriate according to ANSI ASHRAE Standard 55-201. However, the living room's average air temperature fell outside the acceptable range of the Department of Malaysian Standard (2007), the Malaysia Fire Protection Association (2021), and literature from previous authors, which was at 29.4°C.

Indoor relative humidity levels in both rooms were found to be adequate and met the Malaysian Fire Protection Association (2021) regulations, which specified a range of 60% to 70%, and the range imposed by Johari et al. (2021) at 50% to 80%. Johari et al. (2021) conducted a comparative analysis study on naturally ventilated residential buildings between a traditional Malay house and a terrace house, where the findings indicated that the appropriate range for relative humidity lies between 50% and 80%. Table 6 shows that the average relative humidity in bedroom one was 69.3%, whereas the average relative humidity in the living room was 67.6%, which was 1.7% lower.

The Malaysian Fire Protection Association advises maintaining air velocity in the range of 0.15 to 0.50 m/s to create a comfortable thermal environment. Similarly, the Department of Malaysian Standards has also determined an acceptable range of 0.25 to 0.50 m/s, as space will feel fresh at an appropriate temperature within this range. However, neither space was up to par. Averaging at only 0.01 m/s, significantly below the acceptable range, both bedroom 1 and the living room experienced minimal to static air velocity. Despite an air well courtyard being present in the design of the terrace house, neither space had adequate airflow. In conclusion, bedroom 1's thermal environment was generally superior to the living room's. The living room overheated and had poor indoor thermal conditions due to a combination of high temperatures, high relative humidity, and restricted air circulation.

Table 6: Summary on Thermal Environment of Air-Welled Type Courtyard Terrace House.

<table>
<tr><th>Parameter</th><th colspan="3"></th><th>Remarks</th></tr>
<tr><td rowspan="6">Air Temperature (°C)</td><td rowspan="3">Bedroom 1</td><td>Min</td><td>27.7</td><td rowspan="3">1. Did not achieve the acceptable range:
• 23 - 26°C (Malaysia Fire Protection Association, 2021)
2. Complied with the majority of standards:
• 23– 28.69°C (Jamaludin and Izma, 2015, Zain et al, 2007)
• 23.6 – 28.6°C (Steven and Sabarinah, 2007)
• ANSI/ASHRAE Standard 55-2017</td></tr>
<tr><td>Max</td><td>28.8</td></tr>
<tr><td>Average</td><td>28.3</td></tr>
<tr><td rowspan="3">Living Room</td><td>Min</td><td>27.7</td><td rowspan="3">1. Did not achieve the acceptable range:
• 23 -26°C (Department of Malaysian Standard, 2007, Malaysia Fire Protection Association, 2021)
• 23-28.69°C (Jamaludin and Izma, 2015, Zain et al, 2007)
• 23.6 – 28.6°C (Steven and Sabarinah, 2007)
2. Slightly within the range of acceptable standards:
• ANSI/ASHRAE Standard 55-2017</td></tr>
<tr><td>Max</td><td>30.4</td></tr>
<tr><td>Average</td><td>29.4</td></tr>
<tr><td rowspan="2"></td><td rowspan="2">Bedroom 1</td><td>Min</td><td>67.4</td><td rowspan="2">Both bedroom 1 and the living room achieved the acceptable standard:</td></tr>
<tr><td>Max</td><td>71.8</td></tr>
</table>

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Relative Humidity (%RH)		**Average**	69.3	• 50% – 80% (Johari et al, 2021) • 60% - 70% (Malaysian Fire Protection Association, 2021)
	Living Room	**Min**	63.4	
		Max	72.3	
		Average	67.6	
Air Velocity (m/s)	**Bedroom 1**	**Min**	0.01	Both rooms did not comply with the standard acceptable range: • 0.15 – 0.50m/s (Malaysian Fire Protection Association, 2021) • 0.25 – 0.50m/s (Department of Malaysian Standard, 2017)
		Max	0.02	
		Average	0.01	
	Living Room	**Min**	0.01	
		Max	0.13	
		Average	0.01	

4. Discussion

UBBL 1984, Clause 39(1), mandated every room to provide an opening of not less than 10% of the clear floor area of the room for natural light and ventilation. Evidently, bedroom 1 and the living room do not meet this requirement. To control for external factors that may impact the study, both rooms were set up with the same single-sided ventilation strategy. As a result, it was discovered that the opening provision of the living room was 8.6% and that of bedroom 1 was 9.4%. This deficit is not unexpected given that multiple studies, like Ahmad et al. (2011) and Hanafiah (2005), have reported that residential buildings in Malaysia are equipped with openings that do not fulfill the UBBL requirements.

Field measurement was also used to accomplish the second objective. It is an appropriate method to determine the current indoor thermal condition of rooms connected directly to the air-welled courtyard. The second objective is crucial to indicate whether the actual thermal condition of the rooms is good, moderate, or poor by measuring accurate and precise indoor thermal environmental parameters consisting of air temperature, relative humidity, and air velocity. The rooms in question were bedroom 1 and the living room, the only habitable spaces attached to the air well by openings. Both measured rooms are conditioned to similar characters and were simultaneously recorded from 7 a.m. to 7 p.m. using multi-data loggers, velociCalc and sensors. The analysis of the results was based on three days with a clear sky without rain.

After a thorough comparison of the data from both rooms, the living room and bedroom 1 appeared to have opposite results. The living room, with an opening area of 2.2 m² and an opening provision of 8.6%, appears to be overheated due to the high indoor air temperature. With a 9.4% opening provision, bedroom 1 recorded an average air temperature of 28.3°C, which was 1.1°C lower than the living room's temperature. Despite the little difference, the Department of Malaysian Standard (2007) and earlier studies by scholars like Jamaludin and Izma (2015), Zain et al. (2007), and Steven and Sabarinah (2007) determined that the average air temperature in the living room was higher than what was considered acceptable. On the other hand, both rooms had relative humidity levels within permissible limits. The high moisture content met requirements. The average relative humidity contrasted with the average air velocity in both rooms. Both rooms reported an average wind speed of 0.01 m/s, which the Department of Malaysian Standards deems undetectable air movement. Through careful consideration, it was determined that the living room had a poor thermal environment compared to bedroom 1; the living room has a greater indoor air temperature and lacked air velocity, which results in the room overheating with poor air movement inside the space. The findings obtained regarding the poorly ventilated living room could be attributed to its opening size that failed to comply with the UBBL requirements. Multiple authors have similar views regarding the insufficiency of the 10% opening provision mandated by UBBL, for instance Mohd Sahabuddin & Gonzalez-Longo, (2015). They deemed openings lower than the minimum 10% considered inappropriate and in fact recommended a 15% to 20% provision for better ventilation. Ibiyeye & Zalina, (2015) also discovers the ineffectiveness of openings that do not comply with the UBBL standards through field measurement study conducted on five terrace houses located in Putrajaya. Implementing wider openings allows higher ventilation rates (Hassan & Ramli, 2010). In addition, the poor indoor thermal environment of the living room could potentially be caused by lower air pressure entering the room through the air-well. According to Toe & Kubota, (2015), the indoor air velocity and air temperature are affected by the cooling air pressure difference resulting from the air flowing through openings of different sizes. Thus, the findings recorded through the on-site field study responded to the second research question formulated.

The third objective is concluded by citing the difference in opening provision between both rooms as one of the factors that affected the outcomes obtained. The living room's narrow opening had affected its indoor environment, which was high in air temperature and low in air velocity. However, the question raised about the ineffectiveness of the opening provision requirement regulated by UBBL 1984 cannot be ascertained due to the non-compliance of the existing opening of the terrace house.

5. Limitations of Research

Despite its merits, this study has certain constraints, as discovered during the field measurements. First, the number of available vacant terrace houses was limited due to unresponsive and uncooperative homeowners. There was also a shortage of equipment, particularly the multi-data logger. Two of the thermal multi-data loggers available were placed outdoors and in the living room; however, bedroom 1 employed velociCalc to gather data in order to have results that were recorded simultaneously with the living room. Each piece of equipment has similar functions, but the precision varies. In addition, the field measurement was carried out in January, which received substantial amounts of heavy rainfall as it was the peak of the Northeast Monsoon. Thus, only three of the five-day field measurements—the only ones without rain or cloud cover—were studied and analysed. Lastly, since the study centres on the opening size, other courtyard design variants were not considered. Expanding the sample size and duration of the field measurement study for a more longitudinal comparative study may provide more accurate and reliable results.

6. Conclusion

The recurring issue that impacts Malaysia's terrace houses' thermal environment appears to persist today. Even with the presence of an air-welled courtyard to moderate the air temperature, the design of the terrace house itself, particularly the limited openings, has significantly contributed to the poor ventilation performance and poor indoor thermal environment. The findings here imply that the current living room's opening provision, which does not conform to the UBBL 1984 standard, has caused an overheated environment due to high air temperatures trapped indoors and low air movement. This may be caused by the inadequate ventilation permitted by the existing openings, which renders the courtyard ineffective in serving its purpose of improving the indoor conditions of the house. However, its ineffectiveness cannot be ascertained without extensive further study, such as simulation studies to establish the effects of other different opening sizes. Students, developers, architects, and designers could potentially benefit from such a detailed and intricate study on the minimum opening provision, which may help in determining a suitable opening size range that suits their respective building construction. The results may also serve as a future benchmark or directive for the academic community and the built environment. It is also a step in fulfilling the Green Technology Master Plan 2017–2030, which intends to develop green building efforts that incorporate passive and active design principles.

7. Recommendations

The findings of this research have verified the influence of opening provisions on the indoor thermal environment through field measurements. As a result, several suggestions were made for future reference:

a) As daytime happens to be the majority duration of openings left ajar by residents of terrace houses, this research mainly focused on daytime measurement. Thus, it is suggested that future studies explore the indoor thermal environment at night.
b) To optimize and strengthen the justification for the analysis of the effects of different opening sizes on the indoor thermal environment, it is also important to measure the ventilation or air exchange rate (ACH).
c) To improve the ventilation effectiveness of an air well, additional investigation of other air well variants and the opening design, besides the size, could be explored.

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